Comprehensive Machinery Monitoring with FFPI Sensors

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Abstract: This paper introduces the benefits of applying the optical fiber Fabry-Perot interferometer (ffpi) pressure sensor as a means of detecting flow instabilities in centrifugal pumps and compressors. Actual pump test data will be presented, demonstrating how harmful hydraulic instabilities, such as cavitation and low flow instabilities, can be readily detected using this new sensor. The authors will explain how centrifugal compressors can be protected from surge by sensing flow reversals with an ffpi differential pressure sensor. Also covered is how the ffpi pressure sensors can be integrated into a complete ffpi monitoring system capable of sensing bearing housing vibration, shaft vibration, and shaft rotary speed.

Key Words: accelerometer; cavitation; centrifugal compressors; centrifugal pumps; fiber optics; Fabry-Perot interferometer; pressure sensor; surge

Introduction: Today, more than ever, it is vital that we design and operate our process equipment so that catastrophic failures and product releases are extremely rare events. This means that, in addition to purchasing well designed and constructed equipment, we must monitor their condition to ensure they remain healthy during their operational lives. A vibration monitoring program is a common means of protecting mechanical equipment from catastrophic failures. For critical pumps, such as those handling highly flammable or toxic fluids, prudent operation also requires users to monitor pressure pulsations as a means of ensuring proper hydraulic operation and preventing flow related mechanical failures. For centrifugal compressors, dynamic flow fluctuations should be sensed as a

means of protecting them from the dangers of surge. The authors will discuss how it is now possible and practical to monitor both the mechanical condition and hydraulic or aerodynamic condition of high performance centrifugal equipment.

Centrifugal Pump Characteristics: Centrifugal pumps are designed to produce a fairly constant differential pressure at a given flowrate. Idealized head-flow curves give users the illusion that centrifugal pumps generate only static pressure. However, in reality, this class of pump generates a dynamic pressure component along with the static component. This dynamic pressure component is an excellent indicator of how the pump is being operated. Many have tried to use vibration information to detect flow related problems; but this evaluation method is imprecise when it comes to assessing the severity of the flow problem. Dynamic pressure, on the other hand, can be converted to force by knowing the peak to peak pressure magnitude and the impeller's projected area.

A small dynamic pressure component (<10% of the static differential pressure) means there is plenty of net positive suction head available (NPSHA) and that the pump is operating close to its best efficiency point (BEP); but a large dynamic pressure component means the pump is hydraulically unstable [1]. The primary danger of excessive dynamic pressures is that they lead to large dynamic forces causing premature bearing failures and shaft deflections that can lead to wear ring contact and seal failures [2],[3].

Until recently, a continuous-duty dynamic pressure monitoring system was impractical because standard pressure transducers were limited to processes operating below about 300 ^{O}F. With the recent development of the optical fiber Fabry-Perot interferometer (ffpi) pressure sensor, pumps can now be monitored in services operating at much higher temperatures [4]. In the past year, ffpi pressure sensors have been used successfully in harsh process environments with temperatures exceeding 700 ^{O}F.

Pressure Sensor Design: The ffpi sensing element, which is the basis for the pressure transducer, consists of two internal mirrors separated by a length L of single mode optical fiber, as illustrated in Fig. 1. Each mirror is produced by vacuum deposition of a thin film of the dielectric material TiO_2 on the cleaved end of a fused silica (SiO_2) fiber. Electric arc fusion splicing is used to integrate the mirrors, which each have a reflectance of about 5%, into a continuous length of the fiber. For the pressure sensor, L is about 1 cm.

The next step in making a pressure sensor is to embed the ffpi along the axis of an aluminum alloy rod by a casting process. After machining the cast rod to the desired dimensions, it is inserted into a stainless steel housing with a thin (0.5 mm) lower wall. A nut at the top of the housing is torqued to produce a slight compression of the aluminum rod. The sensor is then mounted in a threaded port in the pump inlet or outlet line, as in Fig. 2.

To monitor the sensor, light is coupled into the fiber and a portion of the optical power reflected from the ffpi is converted to an electrical signal by a photodetector. The amplitude of the reflected power, as determined by coherent interference of light reflected from the two mirrors, is very sensitive to small changes in L. The pressure sensor is designed such that the fluid pressure produces a slight strain (of the order of 10 μstrain, or 0.1 μm change in L) in the fiber, leading to a large fractional change in the reflected optical power [4],[5].

System Design: A pressure measurement system developed at FFPI Industries in which one laser provides optical power for up to 24 sensors is illustrated in Fig. 3. Light from a semiconductor laser diode (LD) modulated with a sawtooth waveform is coupled into a single mode fiber and through an optical isolator to prevent feedback into the laser. The laser light is split by a star coupler to provide optical power to each sensor. A portion of the reflected light from each sensor is routed through a directional coupler to a PIN photodiode, which converts the raw optical signal to an electrical signal. The two unprocessed sensor signals are digitized and a microprocessor computes the pressure. The final stage of the signal processor contains a digital-to-analog converter, providing analog pressure vs. time for each sensor. The dynamic pressure response of each sensor is calibrated against a conventional pressure sensor.

Test Setup and Description: To test the ffpi pressure sensor, we chose to monitor a hydraulic performance and net positive suction head (NPSH) test in a pump manufacturer's test facility. In this way, we were able to investigate the effects of low flowrates and actual cavitation. As an added benefit, the owner of the pump asked for a suppression-type NPSH test, which allowed us to assess the effect of falling NPSH on dynamic pressure.

The pump tested was a 6 x 8 x 11 double-suction, overhung process pump rated at 125 hp and 3600 rpm and designed to pump light hydrocarbon liquid in a refinery. The pump was instrumented with an ffpi pressure sensor on the discharge piping and one on the suction piping. At the time, it was not known if dynamic pressure pulsations would be more pronounced on the suction or discharge of the pump. The optical fiber cables from each transducer were then connected to the FFPI signal conditioning unit through optical fiber connectors. The converted electrical signals exiting the signal conditioning unit were connected to a PC for viewing and storage in digital form.

It is important to note that the test pump had a suction specific speed of 11,800 and BEP flow of about 1688 gpm. During the performance test, the pump was operated at flows of 300, 600, 900, 1200, 1600, 1800, and 2000 gpm, while the suction and discharge pressures were recorded. During the NPSH suppression test, the pump flows were held at 300, 1000, 1600, and 1800 gpm, while the effects of NPSH on differential pressure were recorded.

Historically, the onset of cavitation has been detected by a loss of head. The Hydraulic Institute defines NPSH to be the point where a 3% loss of pump differential pressure is observed. In our NPSH test, the flow was held constant while the NPSH was reduced by pulling a vacuum in the test stand suction tank. Once the NPSHA equaled the NPSH required (NPSHR), a drop in discharge pressure was observed. During the 1000 gpm suppression test, for example, the NPSHA was varied from 32 ft down to about 8.4 ft. Since, by testing, the 3% drop in discharge pressure for this flow was found to be about 9.2 ft, we can say the ratio of NPSHA/NPSHR was varied from 3.48 to .91.

Test Results and Conclusions: Several key observations were made from the resulting dynamic pressure waveforms recorded during the pump test. There seemed to be three major categories of pressure pulsations that arose during the test. First, when there was plenty of NPSH available, i.e. NPSHA/NPSHR > 2, there were only rare signs of cavitation. Typically, components of vane pass frequencies and lower were seen. At flows of 50% of BEP flow and less, dynamic pressure pulsation rose to about 30 psi (peak to peak). These types of pulsations are expected during off-design operation due to internal recirculation and inefficient flow distribution in the impeller and cutwaters.

The second category of pressure pulsation seen was of classical cavitation. At all flows, when the NPSHA equaled the NPSHR, high frequency pressure spikes were observed. These pressure spikes were clear signs of vapor bubble implosions in the impeller suction. The magnitude and frequency of occurrence increased at lower values of NPSHA and at lower flows.

The third category of pressure pulsation observed was that of pressure surging. This phenomenon resulted in pulsation frequencies of about 5 Hz and was only detected at flow rates less than 60% of BEP and when the NPSHA equaled the NPSHR (see Fig. 4). At the onset of surging, dynamic pressure amplitudes, at times, exceeded 40 psi (peak to peak). At these lower flows, as the NPSHA fell below the NPSHR, dynamic pressure pulsation became erratic, random, and destructively large (> 80 psi pk-pk), as seen in Fig. 5.

As a result of this testing we can draw the following conclusions:

* Dynamic pressure pulsations increase dramatically whenever a pump is operated at flow significantly below its BEP flow.
* Dynamic pressure pulsations increase dramatically whenever the NPSHA drops to/or below the pump's NPSHR.
* The combination of low flow and NPSHA can lead to excessive and potentially destructive pulsation levels.
* The ffpi pressure sensor has the sensitivity and dynamic response required to sense hydraulic phenomena typically seen during events of cavitation and hydraulic instability.

Monitoring Centrifugal Compressors: Similar to centrifugal pumps, centrifugal compressors are designed to produce a constant discharge pressure for a given flow. The absence of significant pressure pulsations and a predictable differential pressure at a given flow make this class of compressor popular in the chemical process industry. Fig. 6 shows a typical performance map for a centrifugal compressor, where the abscissa is flowrate and the ordinate is discharge pressure. The relationship between discharge pressure and flow is defined by the N curves. N_1, N_2, N_3, and so forth represent the expected compressor performance at different compressor speeds. N_1 represents performance at the highest operating compressor rpm and N_4 represents performance at the slowest operating rpm.

Operation in the region defined by the surge control line and the end of each performance curve will usually ensure safe performance. However, operation to the left of the surge line can result in severe flow surging. Surging is the condition where rapid pulsations in flow occur. At higher discharge pressures, compressors eventually reach a point where they can no longer generate pressure and experience stall. Once the compressor stalls, the compressor flow actually reverses and the discharge pressure drops. (The time for the flow to go from forward flow to reverse flow has been measured at .05 seconds. [6]) As a result of the lower discharge pressure, the compressor is able to reestablish forward flow and does so until the discharge pressure reaches the surge point. This cycle of reverse flow and forward flow repeats itself time and time again until discharge pressure is lowered, suction pressure in raised, or the gas density increases.

The frequency and amplitude of these flow and pressure fluctuations very widely between different classes of centrifugal compressors. Some of the factors affecting these fluctuations are compressor design, i.e. radial flow, axial flow, horsepower rating, and the piping system design. In installations where fluid horsepower is high and the piping and vessel designs are such that fluid energy is readily stored, the potential for destructive flow and pressure pulsations during surging is great.

Probably the most disastrous consequence of surge is its effect on the compressor thrust bearing. Usually, this bearing carries a constant load; but if surge is experienced, the thrust load fluctuates wildly. These rapid and violent changes in thrust load and position have been known to result in thrust bearing failures--and soon after massive compressor rotor damage occurs.

Another consequence of surge dreaded in axial compressors is that of gas reheating. Surging in axial compressors may only occur in a few of the stages. If surge occurs in the later compression stages, the gas is reheated with each surge cycle. This results in a rapid rise in gas temperature and can reach the point where the mechanical properties of the blading degrade--often leading to catastrophic blade failures.

Detecting Surge in Centrifugal Compressors: To avoid surge, it is essential to measure the right process variable. Two of the best process variables to measure are

compressor differential pressure, ΔP_c, and the differential pressure across the gas flow orifice, ΔP_0. Fig. 7 and 8 show typical plots of these variable at the time of a surge event. Notice how quickly these events occur and that ΔP_0 represents a much greater change on a percentage basis. Also notice that after the initial flow reversal a lower frequency flow and pressure surge begins. These sample surge plots suggests that monitoring the flow orifice differential pressure is an effective means of monitoring flow stability.

To sense the rapid pressure fluctuation generated by surge events, a high frequency pressure sensor is required. An ffpi differential pressure sensor possesses the ability to sense high frequency (up to 2 khz) pressure changes, while being immune to high process temperatures. This makes it ideal for high compression ratio applications, where high discharge temperatures can be encountered. A typical ffpi sensor installation is shown in Fig. 9. Sensing ΔP_0 across the inlet flow orifice, as shown, will allow a user to immediately sense a surge event and act quickly upon this information before compressor damage can occur.

Vibration Monitoring Options: To augment ffpi dynamic pressure sensors for monitoring centrifugal pumps and compressors, users can utilize a full array of ffpi machinery monitoring sensors, which will also be immune to electromagnetic interference and high temperatures. This array includes the Fabry-Perot interferometer based accelerometer, bearing defect sensor, proximity probe, and speed sensor.

Fig. 10 shows a typical monitoring scheme for a centrifugal pumps with antifriction bearings [7]. Notice the dynamic pressure transducer in the pump's discharge line for measuring cavitation and flow instability. ffpi accelerometers, used to detect rotor-related vibration, are mounted on the bearings housings. A speed sensing ffpi probe, capable of measuring speed and sensing the direction of rotation, is mounted near the pump's key way. And finally, an ffpi bearing defect probe is mounted near the pump's thrust bearing to sense bearing damage.

Fig. 11 shows a typical monitoring scheme for a centrifugal compressor with sleeve bearings. First, you will notice the ffpi differential pressure sensor mounted across the inlet flow orifice. The purpose of this sensor is to detect the occurrence of surge. A single ffpi pressure sensor can be used at the compressor discharge or between stages to sense pressure pulsations due to impeller damage or off-design operation. Next, there are ffpi proximity probes near the hydrodynamic bearings for sensing shaft vibration, along with a speed sensor. Finally, there is an ffpi proximity sensor at the thrust bearing to ensure that thrust position is maintained.

The configurations shown in Fig. 10 and 11 represent the most comprehensive monitoring schemes available for turbomachinery. They allow users to accurately assess pump and compressor performance--mechanical as well as hydraulic or aerodynamic.

The Future of FFPI Sensors: Ongoing development of fiber optic sensor technology at FFPI Industries and Texas A&M is directed towards establishing long-term

durability, improving sensor capability, and reducing system cost. Durability tests of in-cylinder pressure sensors at operating temperatures in the 200°C - 300°C range in reciprocating engines are continuing. New sensor designs which can extend operating temperatures to 500°C - 800°C range and improve the sensitivities by 1 to 2 orders of magnitude are being investigated. The replacement of laser diodes (LD) in the present signal conditioning units with less expensive light emitting diodes (LED) shows promise as a cost-saving measure.

The widespread use of fiber optic sensors in industrial monitoring and control should become a reality within the next decade. We can envision networks of tens to hundreds of point sensors connected to computers which process the raw optical signals, store parametric data, and implement feedback algorithms in the control of equipment and processes. Fiber optic sensor networks will eliminate electromagnetic pickup problems so common with conventional electrical sensors, and they will enhance safety by making it possible to physically isolate all electrical cables and electronic component from volatile materials. It is anticipated that technology will become affordable in the years ahead as the application ot multiplexing techniques makes it possible to operate an increasing number of sensors and control loops from a single signal conditioning unit.

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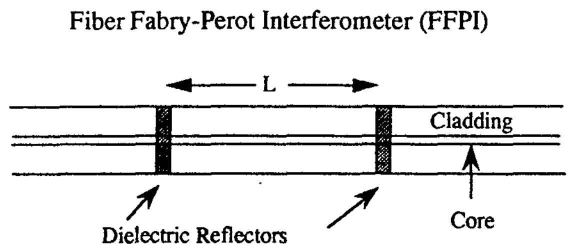


Fig 1 Fiber Fabry-Perot Interferometer

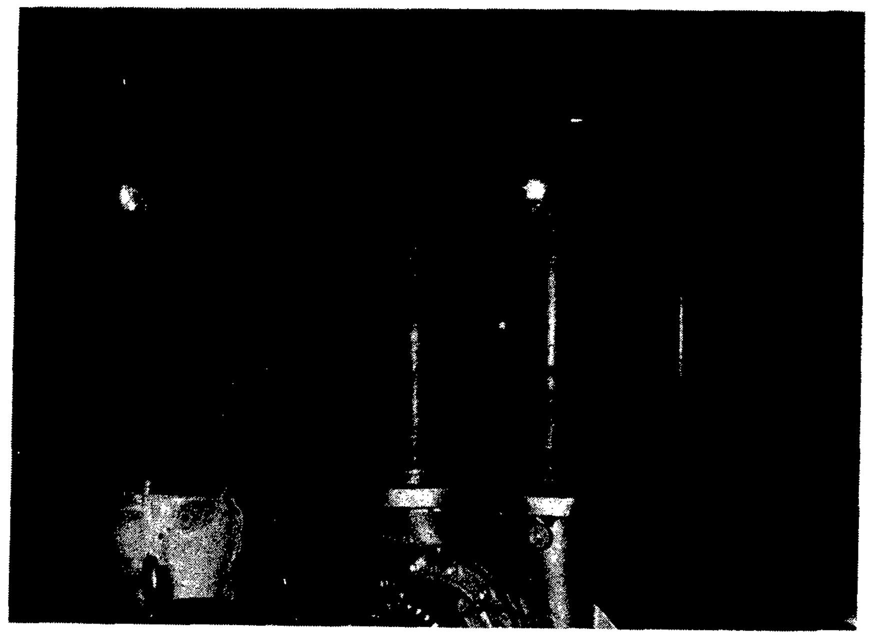


Fig 2 Photo of author standing next to pump

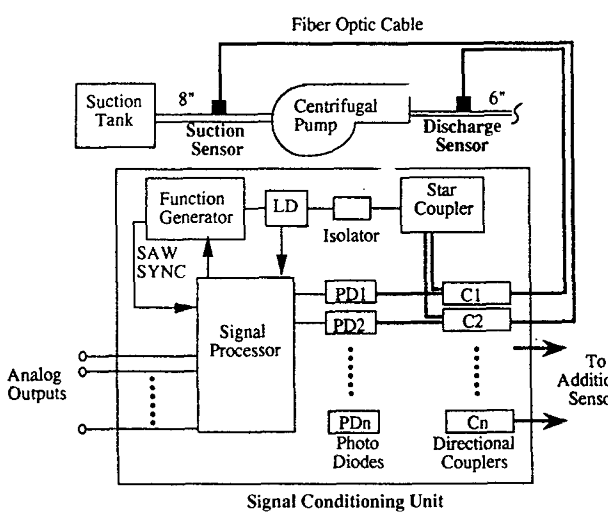


Fig 3 Schematic of pump test arrangement

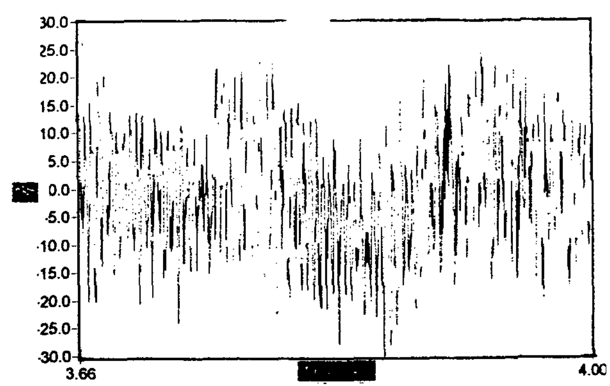
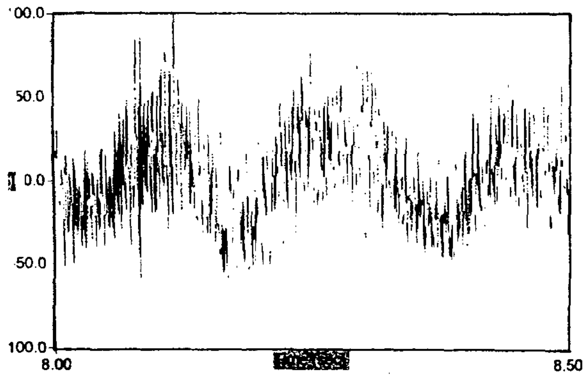


Fig 4 Pressure pulsation at 1000gpm and NRSHA< NRSHR



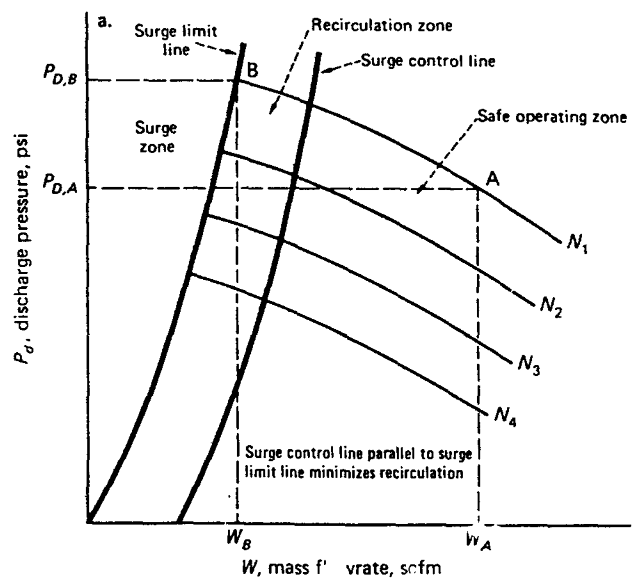


Fig 5 Pressure pulsation at 300gpm and NRSHA<NRSHR

Fig 6 Characteristic curves and surge control lines define regions of operation for compressor

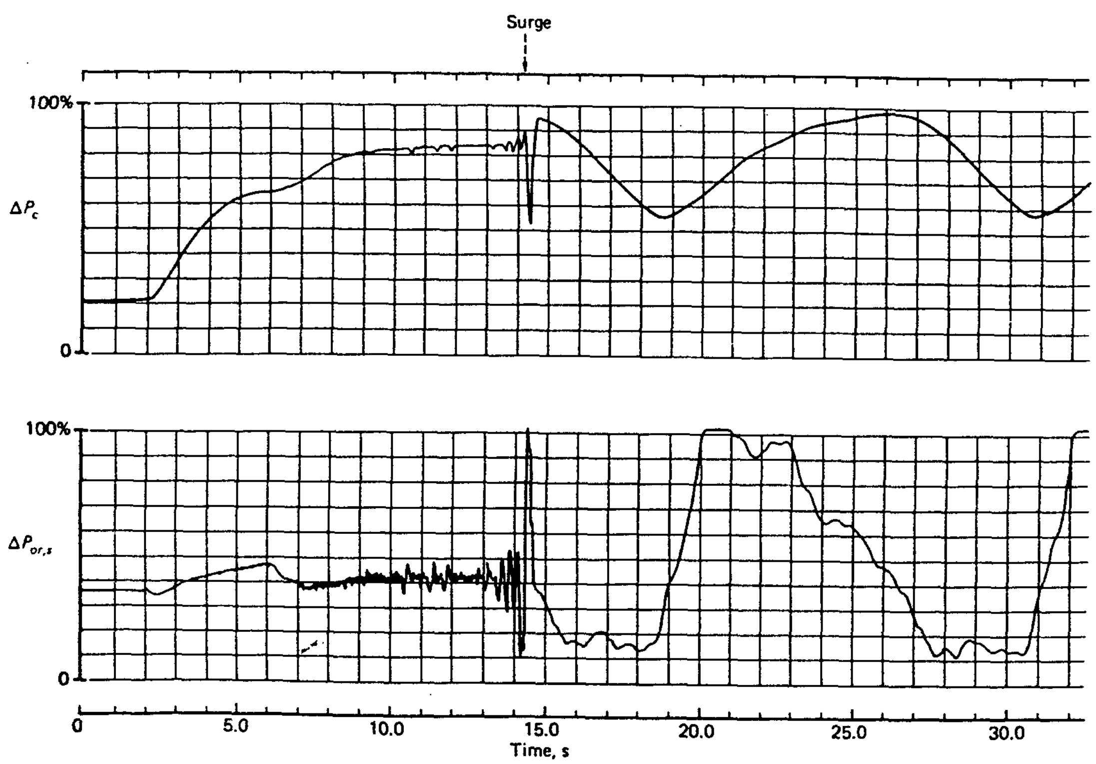


Fig 7,8 Flow drops precipitously before surge cycles begin then reverses quickly

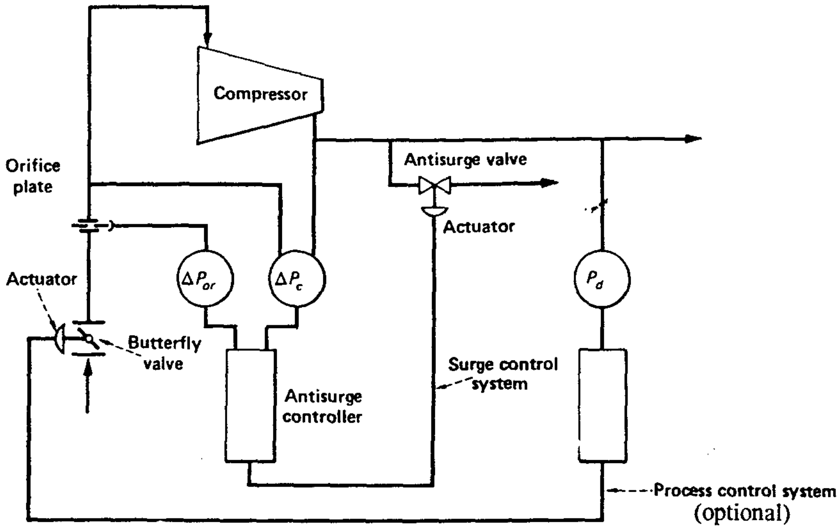
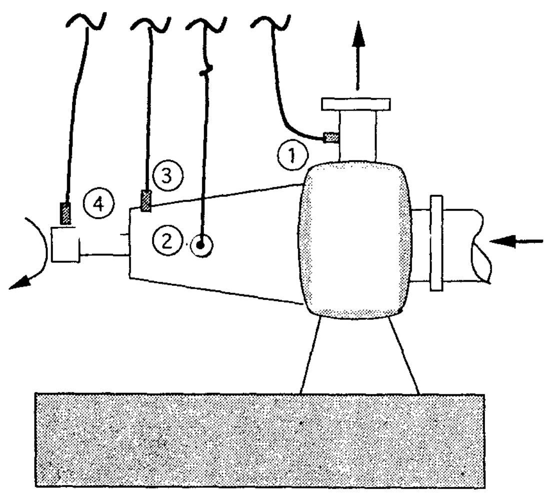
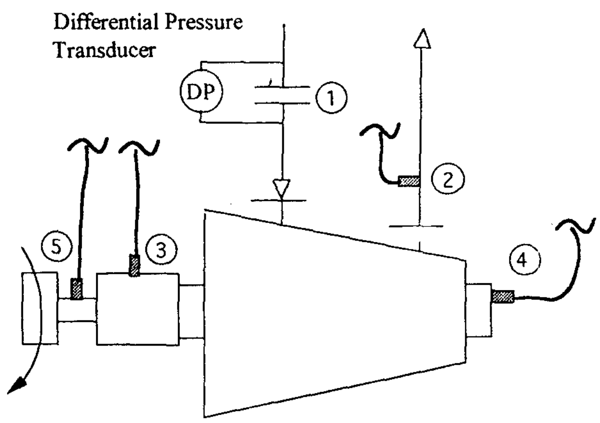


Fig 9 Basic schemes for surge protection



1. Dynamic pressure sensor 2. Accelerometer
3. Bearing defect sensor 4. Speed sensor

Fig 10 Typical pump monitoring arrangement



1. Surge sensor 2. Dynamic pressure sensor
3. Shaft vibration probe 4. Thrust probe
5. Speed sensor

Fig 11 Typical compressor monitoring arrangement